Evaluation of Geothermal Resources in a Hotspot Realm: Mauritius Island (Indian Ocean)

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The Island of Mauritius is the emerging portion of a huge submarine, aseismic, volcanic plateau, which is part of the Africa plate and extends in the SW part of the Indian Ocean. The plateau is related to a long-lived Réunion hotspot track, whose present-day expression is the active volcano of La Réunion Island, located about 200 km SW of Mauritius.

La Réunion Island, has no topographic continuity with the swell and consists of a broad elliptic volcanic shield.

The two Islands are bounded by two fracture zone (FZ), Mahanoro to the west and Mauritius to the east.

Position of the Seychelles-Mascarene plateau (SMP), superimposed on a map of seafloor age (colour scale in Ma) by Müller et al. (2008). Black line is the -2500 m observed topographic contour. White boxes show ages of hotspot volcanism (in Ma) after Duncan and Hargaves (1990) and Tiwari et al. (2007). Continental lithosphere in grey.
INTRODUCTION

The hotspot track is characterised by age-progressive volcanic centres, which have migrated from north to south since 65 Ma ago to the Present. The hotspot activity has affected an old (40-90 Ma; Müller et al., 2008) and thick lithosphere.

La Réunion and Mauritius islands show volcanic activity spanning in age 0-3 Ma and 0.03-8 Ma, respectively (Moore et al., 2011). This indicates a rather long period of simultaneous volcanic activity on the two islands. Such a regional volcanism during the last 3-5 Ma likely requires a complex melt distribution at depth (Barruol and Fontaine, 2013).

Volcanism of Mauritius and the nearby La Réunion is probably fed by the same magmatic source (Demange et al., 1989).

Recent geological, geochemical and geophysical investigations aimed at the evaluation of geothermal resources of Mauritius:

a) Geochemical Survey was carried out to investigate the interaction groundwater/possible magmatic system; b) Geothermal Investigations (thermal logging in a gradient hole and some water wells) supply Information on the thermal regime present in the island.
Mauritius corresponds to the minor dry land area of a typical, huge polygenic shield volcano, built on oceanic seafloor. Volcanic type and overall morphology of Mauritius determine a general outward dipping of the main volcanostratigraphic discontinuities. This feature should be considered in any hydrogeological model.

The available volcanological data of Mauritius claim the presence of a caldera structure in the central part of the island (Paul et al., 2007)

Volcanism has developed on Mauritius during three phases, dated 7.8-5.5 Ma, 3.5-1.9 Ma, and 0.7-0.03 Ma, which are termed:

- **Older Series** (mainly olivine basalt)
- **Intermediate Series** (mainly hawaiites and mugearites)
- **Younger Series** (mostly olivine basalts with smaller volumes of basanites) (Paul et al., 2007; Moore et al., 2011)
Similarly to La Réunion (Michon et al., 2007), important fracture systems are observed, because of the combination of rigid rock types (i.e. basaltic lavas) and the extensional to strike-slip tectonics and subsequent faulting and fracturing.

All Mauritius geodynamic models highlight a dense set of deep-seated fracture/fault zones. This is considered as a regional-scale feature, which may produce high permeability conditions, i.e. favorable to potential geothermal resources (ELC, 2014).

In Mauritius Is., the total absence of geothermal manifestations seems to indicate that possible heat sources cannot be shallow magmatic chambers (may reside in deep-reaching fracture zones).

This may hinder the interaction between the possible deep heat source and the infiltrating water.

The central part of Mauritius Island (youngest volcanic events dated 0.03 Ma ago) is the most suitable to the assessment of the geothermal potential.
Twenty-nine (29) water samples were collected from boreholes drilled at shallow depths for different purposes, including domestic, agricultural and industrial uses. Chemical and Isotopic analyses were performed. Moreover, TDIC, TDIC speciation, CO\textsubscript{2} partial pressure and saturation index (SI) with respect to calcite were determined.

The geochemical data allowed:

i. the definition of the water chemistry

ii. the calculation of the speciation-saturation, identifying the distribution of CO\textsubscript{2} partial pressure, and the saturation index with respect to calcite

iii. characterising the origin of groundwater

iv. estimating the reservoir temperatures with water geothermometers

<table>
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<tr>
<th>Sample</th>
<th>T °C</th>
<th>pH</th>
<th>Na (\mu)S cm(^{-1})</th>
<th>K mg/l</th>
<th>Mg mg/l</th>
<th>Ca mg/l</th>
<th>SO\textsubscript{4} mg/l</th>
<th>Cl mg/l</th>
<th>SiO\textsubscript{2} mg/l</th>
<th>Fe mg/l</th>
<th>(\delta^{18}O) ‰ vs.VSMOW</th>
<th>(\delta D) ‰</th>
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Results of chemical and isotopical analyses on water samples. T – temperature; \(\sigma\) – electrical conductivity; VSMOW – Vienna Standard Mean Ocean Water

<table>
<thead>
<tr>
<th>Sample</th>
<th>T °C</th>
<th>pH</th>
<th>Alkalinity mg HCO\textsubscript{3}/l</th>
<th>TDIC HCO\textsubscript{3} mol/l</th>
<th>TDIC CO\textsubscript{2} mol/l</th>
<th>CO\textsubscript{2} P\textsubscript{CO2} bar</th>
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</table>

Total dissolved inorganic carbon (TDIC), TDIC speciation, partial pressure of CO\textsubscript{2} and saturation index SI with respect to calcite, for water samples from boreholes of Mauritius Island. Total alkalinity values reported in bold were measured in the field.
Most of the collected samples are HCO$_3$ waters with in general comparable concentrations of Ca, Mg, and Na, low-salinity (2.1 to 9.6 meq/l), and low outlet temperature (23 to 29 °C).

They are originated through dissolution of local volcanic rocks, mainly those of the younger series, driven by conversion of aqueous CO$_2$ to HCO$_3$-ion.

The cumulative distribution of CO$_2$ partial pressure shows a population with lower values (0.0513-0.0108 bar), ascribable to decay of organic matter and root respiration in soils, and a population with larger values (0.1160-0.0564 bar), probably a mixture of shallow and deep contributions.

In any case, the involvement, even partial, of one or more deep CO$_2$ sources does not necessarily implies the presence of a geothermal system at shallow-intermediate depth. In fact, due to the very low solubility of CO$_2$ in magmas, the flux of deep CO$_2$ may result from magmatic degassing, occurring at great depth.
The $\delta^D$ and $\delta^{18}O$ values of all the groundwater samples are within the ranges of the local rainwater, indicating a meteoric origin. In addition, there is no oxygen isotope shift as it usually occurs in many geothermal waters (Giggenbach, 1991 and 1992).
The triangular Mg-K-Na diagram is differently scaled with respect to the original plot proposed by Giggenbach (1988) to shift the data points towards the center of the diagram.

All the samples plot in the field of immature waters.

The temperature of the aquifer of immature waters can be obtained by using the K-Mg geothermometer, provided that they are not too acidic (Giggenbach, 1988).

Excluding samples 729 and 789 (as they are unusually rich in Na and K, respectively, due to ion exchange during freshening and anthropogenic pollution) and applying the K-Mg geothermometer (i.e., drawing a line connecting a given sample with the Na vertex), equilibrium temperatures of 5-36 °C are obtained.

Although the meaningfulness of these temperatures is dubious, they do not deviate too much from outlet temperatures.

There is no geochemical indication on the possible presence of a geothermal system at depth in the explored area of Mauritius Is. and chemical features are ascribable to short-term water-rock interaction in shallow hydrological circuits.

However, it cannot be ruled out that a deep heat source, hydraulically insulated from shallow aquifers, can occur.
A 270 m deep hole was drilled in the central part of the island for downhole temperature measurements and the evaluation of the geothermal gradient. The well site is located at 416 m a.s.l. along the ENE flank of Bar Le Duc - L'Escalier polygenic volcano in the central part of the island and lies inside the rim of the inferred caldera structure.

A drilling depth of 500 m was initially planned for BH1226. This depth was suggested to avoid possible influences of shallow, cold aquifers on the measured temperatures and to provide reliable information of the true deep thermal gradient. Actually, several water strikes at different depths were noticed during drilling. Water inflows occurred at about 60 m, 120 m and 180 m depth.

Unfortunately, due to technical problems encountered while drilling the target depth of the gradient well was not achieved. Drilling stopped at 432 m bsl and casing was inserted only to about 270 m depth.
From the lithological viewpoint, the hole encountered a sequence of basaltic lava flows and pyroclastic deposits, belonging to the three chronologically distinct magmatic cycles (Older, Intermediate and Younger Series), with thin intercalations of laterite (paleosoil?), which was considered as a marker of the main volcanic cycles.

Down-hole temperature logs were carried out in the 270 m cased section of the hole and temperature was recorded at 5-m depth intervals by means of a precision temperature acquisition system with an uncertainty of ~ 0.01 K.

Thermal log shows significant perturbation due to groundwater flow, especially between 150 and 210 m, which causes distortion of the temperature depth profile and therefore biases the inference of the geothermal gradient in the upper section of the hole.

Actually, it is observed that thermal gradient is negative at shallow depth, then it is relatively constant between 40 and 110 m; in the interval 110-210 m the largest variations of gradient, often turning to negative, occur. **Below 210 m the gradient appears to be quite constant**

The deeper level appears to be in a purely conductive thermal regime with an estimated thermal gradient of 43°C km⁻¹ (extrapolating a temperature of 180 °C at a depth of about 4,000 m).
Comparative measurements were also made in a water well (BH740) 10 km far from BH1226, no longer used for extraction. The well is 170 m deep and has the water table at 13 m b.g.l. As shown in the Figure here below, a null gradient was recorded up to 95 m, followed by a gradient of 20-40 °C km⁻¹ in the 95-115 m interval, which is consistent with the conductive gradient inferred in the deepest part of BH1226. Below this level gradient turns again to null or negative and increases again in the last twenty meters.

Such thermal gradient distribution can be interpreted as due to the presence of thin impermeable layers sandwiched between pervious horizons where intense groundwater circulation is taking place.

In conclusion:

*thermal measurements indicate the absence of a significant thermal anomaly in the sector of Mauritius singled out as the most favourable for geothermal resources*
The Mauritius Is. is characterized by intense and recent tectonic activity, which produced widespread fracturing and hence adequate permeability of the lavic formations. All available geological information indicated that the central part of the island is the most favorable to host a geothermal system. However, chemical characters of water samples show only short-term water-rock interactions in shallow circuits.

The down-hole temperature logs run in a gradient hole yielded a thermal gradient of 43 °C km⁻¹. Such a value exceeds by only about 1.3 times the “normal” geothermal gradient. Another attempt of assessing the geothermal gradient in a water well drilled in the same area confirmed the presence of a weak or null deep-seated thermal anomaly beneath Mauritius Island.

Although Mauritius volcanism was active until 0.03 My ago, the comparison of the geothermal gradient from offshore measurements in the Mascarene Plateau shows that the gradient measured in Mauritius is even lower than that observed in the 60-80 My old oceanic lithosphere (Chiozzi et al., 2015). This might mean that the deep thermal processes (mantle plume) invoked to occur in the Mascarene hotspot area do not likely yield any particular thermal signature.

Temperature logging in La Réunion Is. revealed a geothermal gradient relatively larger than Mauritius, which however exceeds by only 1.7-2.8 times the world average (Demange et al., 1989). Moderate thermal anomalies seem a common feature in the geological environment of Ocean Islands. Geothermal heat sources in basaltic volcanoes of ocean islands (hotspot areas) rely on frequent but small eruptions. In contrast, along convergent plate boundaries and on the continents, eruptions are less frequent, but heat sources are shallow and large (Wohletz and Grant, 1992). Therefore, in spite of the still present volcanic activity, it is not surprising that moderate thermal anomalies were found in La Réunion.

This strengthens the observation that the geothermal gradient of Mauritius, in which active volcanism is even lacking, is only slightly larger than normal one and thus consistent with the volcanic evolution and migration of the Mascarene hotspot.
Thank you for your kind attention

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